

1 Fitness tracking reveals task-specific associations  
2 between memory, mental health, and exercise

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8 **Abstract**

9 Physical exercise can benefit both physical and mental well-being. Different forms of exercise  
10 (i.e., aerobic versus anaerobic; running versus walking versus swimming versus yoga; high-  
11 intensity interval training versus endurance workouts; etc.) impact physical fitness in different  
12 ways. For example, running may substantially impact leg and heart strength but only moderately  
13 impact arm strength. We hypothesized that the mental benefits of exercise might be similarly  
14 differentiated. We focused specifically on how different forms of exercise might related to different  
15 aspects of memory and mental health. To test our hypothesis, we collected nearly a century's  
16 worth of fitness data (in aggregate). We then asked participants to fill out surveys asking them  
17 to self-report on different aspects of their mental health. We also asked participants to engage in  
18 a battery of memory tasks that tested their short and long term episodic, semantic, and spatial  
19 memory. We found that participants with similar exercise habits and fitness profiles tended to  
20 also exhibit similar mental health and task performance profiles.

## 21 Introduction

22 Engaging in physical activity (exercise) can improve our physical fitness by increasing muscle  
23 strength (Crane et al., 2013; Knuttgen, 2007; Lindh, 1979; Rogers and Evans, 1993), increasing bone  
24 density (Bassey and Ramsdale, 1994; Chilibeck et al., 2012; Layne and Nelson, 1999), increasing  
25 cardiovascular performance (Maiorana et al., 2000; Pollock et al., 2000), increasing lung capac-  
26 ity (Lazovic-Popovic et al., 2016) (although see Roman et al., 2016), increasing endurance (Wilmore  
27 and Knuttgen, 2003), and more. Exercise can also improve mental health (Basso and Suzuki, 2017;  
28 Callaghan, 2004; Deslandes et al., 2009; Mikkelsen et al., 2017; Paluska and Schwenk, 2000; Raglin,  
29 1990; Taylor et al., 1985) and cognitive performance (Basso and Suzuki, 2017; Brisswalter et al.,  
30 2002; Chang et al., 2012; Etnier et al., 2006).

31 The physical benefits of exercise can be explained by stress-responses of the affected body tis-  
32 sues. For example, skeletal muscles that are taxed during exercise exhibit stress responses (Morton  
33 et al., 2009) that can in turn affect their growth or atrophy (Schiaffino et al., 2013). By comparison,  
34 the benefits of exercise on mental health are less direct. For example, one hypothesis is that ex-  
35 ercise leads to specific physiological changes, such as increased aminergic synaptic transmission  
36 and endorphin release, which in turn act on neurotransmitters in the brain (Paluska and Schwenk,  
37 2000).

38 Speculatively, if different exercise regimens lead to different neurophysiological responses, one  
39 might be able to map out a spectrum of signalling and transduction pathways that are impacted  
40 by a given type, duration, and intensity of exercise in each brain region. For example, prior work  
41 has shown that exercise increases acetylcholine levels, starting in the vicinity of the exercised  
42 muscles (Shoemaker et al., 1997). Acetylcholine is thought to play an important role in memory  
43 formation (Palacios-Filardo et al., 2021, e.g., by modulating specific synaptic inputs from entorhinal  
44 cortex to the hippocampus, albeit in rodents;). Given the central role of these medial temporal  
45 lobe structures play in memory, changes in acetylcholine might lead to specific changes in memory  
46 formation and retrieval.

47 In the present study, we hypothesize that (a) different exercise regimens will have different,

48 quantifiable impacts on cognitive performance and mental health, and that (b) these impacts will  
49 be consistent across individuals. To this end, we collected a year of fitness tracking data from  
50 each of 113 participants. We then asked each participant to fill out a brief survey in which they  
51 self-evaluated several aspects of their mental health. Finally, we ran each participant through a  
52 battery of memory tasks, which we used to evaluate their memory performance along several  
53 dimensions. We examined the data for potential associations between memory, mental health, and  
54 exercise.

## 55 Results

- 56 • exploratory analysis (correlations)
  - 57 – Memory-memory
  - 58 – fitness-fitness
  - 59 – survey-survey
  - 60 – (fitness + survey)-memory
- 61 • predictive analysis (regressions)
  - 62 – Predict memory performance on held-out task from other tasks
  - 63 – Predict memory performance on each task using fitness data
  - 64 – Predict memory performance on each task using survey data
- 65 • Reverse correlations: look at recent changes versus baseline trends
  - 66 – Fitness profile that predicts performance on each task (barplots + timelines)
  - 67 – Fitness profile for each survey demographic (barplots + timelines)
  - 68 \* Select out mental health demographics (based on meds, stress levels)

## Discussion

- summarize key findings
- correlation versus causation
- what can vs. can't we know? we can identify correlations, but not causal direction— e.g. we cannot know whether exercise *causes* mental changes versus whether people with particular neural profiles might tend to engage in particular exercise behaviors. that being said, we *can* separate out baseline tendencies (e.g., how people tend to exercise in general) versus recent changes (e.g., how they happened to have exercised prior to the experiment).
- related work (exercise/memory, exercise/mental health), what this study adds
- future direction: towards customized physical exercise recommendation engine for optimizing mental health and mental fitness

## Methods

We ran an online experiment using the Amazon Mechanical Turk platform. We collected data about each participant's fitness and exercise habits, a variety of self-reported measures concerning their mental health, and about their performance on a battery of memory tasks. We mined the dataset for potential associations between memory, mental health, and exercise.

## Experiment

### Participants

We recruited experimental participants by posting our experiment as a Human Intelligence Task (HIT) on the Amazon Mechanical Turk platform. We limited participation to Mechanical Turk Workers who had been assigned a "Masters" designation on the platform, given to workers who score highly across several metrics on a large number of HITs, according to a proprietary algorithm

91 managed by Amazon. We further limited our participant pool to participants who self-reported that  
92 they were fluent in English and regularly used a Fitbit fitness tracker device. A total of 160 workers  
93 accepted our HIT in order to participate in our experiment. Of these, we excluded all participants  
94 who failed to log into their Fitbit account (giving us access to their anonymized fitness tracking  
95 data), encountered technical issues (e.g., by accessing the HIT using an incompatible browser,  
96 device, or operating system), or who ended their participation prematurely, before completing the  
97 full study. In all, 113 participants remained that contributed usable data to the study.

98 For their participation, workers received a base payment of \$5 per hour (computed in 15  
99 minute increments, rounded up to the nearest 15 minutes), plus an additional performance-based  
100 bonus of up to \$5. Our recruitment procedure and study protocol were approved by Dartmouth's  
101 Committee for the Protection of Human Subjects.

102 **Gender, age, and race.** Of the 113 participants who contributed usable data, 77 reported their  
103 gender as female, 35 as male, and 1 chose not to report their gender. Participants ranged in age  
104 from 19–68 years old (25<sup>th</sup> percentile: 28.25 years; 50<sup>th</sup> percentile: 32 years; 75<sup>th</sup> percentile: 38  
105 years). Participants reported their race as White (90 participants), Black or African American (11  
106 participants), Asian (7 participants), Other (4 participants), and American Indian or Alaska Native  
107 (3 participants). One participant opted not to report their race.

108 **Languages.** All participants reported that they were fluent in either 1 and 2 languages (25<sup>th</sup>  
109 percentile: 1; 50<sup>th</sup> percentile: 1; 75<sup>th</sup> percentile: 1), and that they were “familiar” with between 1  
110 and 11 languages (25<sup>th</sup> percentile: 1; 50<sup>th</sup> percentile: 2; 75<sup>th</sup> percentile: 3).

111 **Reported medical conditions and medications.** Participants reported having and/or taking med-  
112 ications pertaining to the following medical conditions: anxiety or depression (4 participants),  
113 recent head injury (2 participants), high blood pressure (1 participant), bipolar (1 participant),  
114 hypothyroidism (1 participant), and other unspecified medications (1 participant). Participants  
115 reported their current and typical stress levels on a Likert scale as very relaxed (-2), a little relaxed  
116 (-1), neutral (0), a little stressed (1), or very stressed (2). The “current” stress level reflected par-

117 participants' stress at the time they participated in the experiment. Their responses ranged from -2  
118 to 2 (current stress: 25<sup>th</sup> percentile: -2; 50<sup>th</sup> percentile: -1; 75<sup>th</sup> percentile: 1; typical stress: 25<sup>th</sup>  
119 percentile: 0; 50<sup>th</sup> percentile: 1; 75<sup>th</sup> percentile: 1). Participants also reported their current level of  
120 alertness on a Likert scale as very sluggish (-2), a little sluggish (-1), neutral (0), a little alert (1),  
121 or very alert (2). Their responses ranged from -2 to 2 (25<sup>th</sup> percentile: 0; 50<sup>th</sup> percentile: 1; 75<sup>th</sup>  
122 percentile: 2).

123 **Residence and level of education.** Participants reported their residence as being located in the  
124 suburbs (36 participants), a large city (30 participants), a small city (23 participants), rural (14 partic-  
125 ipants), or a small town (10 participants). Participants reported their level of education as follows:  
126 College graduate (42 participants), Master's degree (23 participants), Some college (21 partici-  
127 pants), High school graduate (9 participants), Associate's degree (8 participants), Other graduate  
128 or professional school (5 participants), Some graduate training (3 participants), or Doctorate (2  
129 participants).

130 **Reported water and coffee intake.** Participants reported the number of cups of water and coffee  
131 they had consumed prior to accepting the HIT. Water consumption ranged from 0–6 cups (25<sup>th</sup>  
132 percentile: 1; 50<sup>th</sup> percentile: 3; 75<sup>th</sup> percentile: 4). Coffee consumption ranged from 0–4 cups (25<sup>th</sup>  
133 percentile: 0; 50<sup>th</sup> percentile: 1; 75<sup>th</sup> percentile: 2).

## 134 **Tasks**

135 **Intake survey.**

136 **Free recall.**

137 **Naturalistic recall.**

138 **Foreign language flashcards.**

139 **Spatial learning.**

140 **Fitness tracking using Fitbit devices**

141 **Processing Fitbit data**

142 **Raw metrics.**

143 **Comparing recent versus baseline measurements.**

144 **Exploratory correlation analyses**

145 **Imputation and interpolation of missing data.**

146 **Regression-based prediction analyses**

147 **Reverse correlation analyses**

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## 155 **Data and code availability**

156 All analysis code and data used in the present manuscript may be found [here](#).

## 157 **Author contributions**

158 Concept: J.R.M. Experiment implementation and data collection: G.M.N. Analyses: G.M.N., E.C.,  
159 P.C.F., and J.R.M. Writing: J.R.M.

## 160 **Competing interests**

161 The authors declare no competing interests.

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